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Further observation of condensation trails

by

N. C. Helliwell and J. K. Mackenzie

(Meteorological Office)

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

M.O.15/31

To all recipients of M.R.P.979

Will you please amend your copy of M.R.P.979 as follows:-

Table I, 11/11/55 (4th line from end of table):

Delete	37,700	209	- 62.2	- 69.4	36.0
Replace by	40,000	187	- 55	- 76.6	5.1

Will you also please replace Figures 1 and 7 by the revised diagrams attached.

Secretary
Meteorological Research Committee

Meteorological Office (M.O.15),
Air Ministry,
London, W.C.2
28th February, 1957

G.5525/AP/2/57/270

At the time of issue this report has not been published. Any author desiring to quote this paper should refer to it as "A paper of the Meteorological Research Committee (London).
M.R.P. No.979 by Messrs. N.C. Helliwell and J.K. Mackenzie
A copy is available in the Library of the Meteorological Office."

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Further observation of condensation trails

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Summary

Two methods of observing condensation trails from a Canberra aircraft are described. The results of the observations made in 1955 are presented and broad estimates of the length of trails are made. The results, presented graphically, attempt to delineate zones in which long and short trails are formed. An empirical forecasting procedure applicable to Canberra aircraft, and based on these data, is suggested.

Introduction

During 1955 several flights were made in a Canberra aircraft of the Meteorological Research Flight to examine the physical conditions governing the formation of condensation trails. Since the crew in this aircraft are so positioned that they cannot look backwards and see the trail it makes, two indirect methods have been used for observing the trail:-

(a) A second aircraft is used to observe the trails of the aircraft carrying the meteorological observer, who takes simultaneous readings of temperature, frost point, height, airspeed and engine setting.

(b) A camera has been mounted in the tail cone of the Canberra aircraft so that by remote control, photographs of the trail behind the aircraft could be taken.

A third method using some form of periscope could have been employed but the camera installation proved to be more practical.

Using either or both of the first two methods several flights were made and the results are presented in a form which it is hoped will be of value to the forecaster and for use in further theoretical studies of contrail formation by jet aircraft.

Methods

(1) A Canberra aircraft equipped with a Dobson-Brewer frost point hygrometer and a standard flat plate thermometer ascended until condensation trails were observed from an accompanying aircraft. The Canberra descended slowly to the level at which trails were just forming and measurements of frost point, temperature, height, airspeed and engine setting were taken at this level. In some flights the Canberra descended a further 1,000 ft. and a further set of readings was taken in conditions of no contrails. The aircraft then climbed slowly on a different engine setting and the observations were repeated at the level at which trails just formed. The aircraft ascended 1,000 ft. above this second level and the observations were repeated. On some occasions observations were made at 1,000 ft. intervals from base of trails to top of trails and then a further set of readings was taken 1,000 ft. above this. Photographs were taken whenever possible by the observer in the accompanying aircraft and it was hoped that the length of trails could be derived from these photographs. One or two were successful but generally the results do not justify inclusion at the present stage and it has been decided to

classify the trails as long, medium and short as described below.

(2) In the second method a camera, mounted in the tail cone and facing backwards, was electrically operated from the pressure cabin by a push button as required. To obviate fogging, the end of the tail cone was fitted with a heated glass window, and to prevent the camera freezing or failing to obtain photographs on account of ice formation on the lens, a special heater muff was designed and fitted.

Whenever a high-level ascent was made to measure humidity, or on the occasions when the aircraft was used to observe contrails by Method (1), photographs were taken at 500 ft. intervals during the ascent and at one minute intervals in level flight. During the high-level ascents temperature was measured on most occasions at intervals of 1,000 ft. and frost points were obtained at 2,000 to 4,000 ft. intervals. The pilot had previously been asked to bank the aircraft at certain specified heights so that when the photographs were developed it would be easier to check the heights at which individual photographs were taken against the log of the observer.

Accuracies

Temperature, height, airspeed and frost point were measured to the accuracy quoted in M.R.P.877 (1) and M.R.P.930 (2), the standard errors being 2°C., 200 ft., 10 knots, and 3°C. respectively. In Method (1) the pressure-height of formation can be found to 50 ft. In Method (2) the heights of the first and last photographs on which trails were just visible were taken to be the lowest and greatest heights at which contrails formed.

Results

Table I and Fig.1 give the basic data for the occurrence of the contrail bases (29 cases) and tops (8 cases). The MINTRA line printed on M.O. Form 2810A (1949 Edition) is shown for comparison on Fig. 1. The data from Method (1) correspond with the observer's log and the data from Method (2) refer to the photograph on which trails were first visible.

Figs.2, 3 and 4 show the results of three typical ascents in which observations were made by Method (2) and illustrate respectively

(1) a case with a well-defined layer in which contrails formed,

(2) a case in which the aircraft had not ceased to make trails at 48,000 ft. and

(3) a marginal case in which trails barely formed.

In each case photographs were taken at 500 ft. intervals as described above and a selection of photographs is shown for various heights.

Fig.2 shows the results of an ascent on 8th November, 1955 in which contrails formed in a band from 29,000 ft. to 40,000 ft. A layer of thin cirrus at 344 mb. (28,000 ft.) can be seen on photograph (a) and this has become a more distinct band on (b). The contrails are only just visible on (b) and this suggests that they were short and very faint. On photograph (c) the trails are more dense and probably of medium length. The change from white trails to grey or black trails is due to the different angle of illumination by the sun. This effect can be used as an additional check on the height at which photographs were taken if the heading is known. Contrails are easily visible to 40,000 ft. (photographs (d) to (f)). They then become short and dense (photograph (g)) and at 40,500 ft. no trails are visible (photograph (h)). At 47,000 ft. (photograph (i)) there are similarly no trails visible.

Fig.3 is an ascent to 48,000 ft. on 28th November, 1955. A band of thin cirrus from 27,000 ft. to 33,000 ft. was noted by the observer and long trails

/were

were first visible at 29,500 ft. (photograph (b)). The records show that trails were still forming up to the maximum height of the ascent, 48,000 ft. (photographs (c) to (h)).

On 1st December, 1955 both methods were employed to find the base and top of condensation trails. A band of dense cirrus was present to 27,000 ft. being continuous from an altostratus layer below. In the accompanying aircraft the observer saw long dense trails at 28,000 ft. on the ascent but these ceased at 28,200 ft. and reappeared at 32,000 ft. in a narrow band. No further trails were observed during the ascent to 48,000 ft. The photographs shown in Fig.4 were taken during the descent which took place in a different area from the ascent. No trails formed between 48,000 ft. and 36,000 ft. A narrow band of trails is just visible on photographs (h) to (j) (34,000 to 35,000 ft.) although these are short and faint and yet another layer is shown on photographs (b) to (d) (25,500 to 26,500 ft.). The trails forming in the cirrus cloud appeared from the other aircraft to be very persistent and long.

The photographic records were examined for lengths by a subjective method. The geometry of the camera optics was used to define three types of trail (1) long, (2) medium and (3) short. It is not easy to be sure that the trails put in any particular classification definitely belong to that class but, in the main, there is little difficulty in distinguishing long and short trails from these photographs. On all occasions temperatures and frost points were available corresponding to certain levels within and along the boundary of the band of contrails and all photographs of trails obtained by Method (2) within this band were classified as above, i.e., intermediate observations as well as those of tops and bases.

Fig.5 shows the depression of the temperature from the MINTRA value at the pressure level corresponding to any photograph plotted against the depression of the frost point from ambient temperature at that level. Long trails are marked by a triangle, medium trails by a dot and short trails by a cross, while cases of no contrail are marked by a square. If an observation was available at the tropopause it is marked T and a circle is drawn round observations taken in the stratosphere. Zones of short and long contrails in the troposphere and stratosphere have been sketched in from the data. From this diagram it is possible to forecast the length of the contrail which will be formed by a Canberra aircraft at any height where the temperature and frost point are known or can be estimated.

Figs.6(a) & 6(b) are frequency diagrams for long, medium and short trails showing the number of observations in 2°C. bands of depression of temperature below MINTRA and 2°C. bands of depression of frost point below ambient temperature. For comparison the measurements of temperature and frost point made 500 ft. and 1,000 ft. below the base and above the top of the layer of contrails are shown as "cases of no contrails". The diagrams 6(a) show that, subjective though the criteria of lengths were, a short contrail may be expected to form at a higher temperature than a long trail. This is not surprising in itself but since the humidity diagrams 6(b) show little variation of length with depression of frost point, the inference can be drawn that the length of the trail is dependent principally on the temperature. It is interesting to note that trails in the stratosphere can be long if the temperature is sufficiently low and the depression of the frost point is not too great.

Fig.7 shows the few observations of engine setting plotted against temperature difference from MINTRA at the height at which trails first form. All these settings are for Canberra aircraft and the results show no connexion between the height at which trails first form and engine power.

Type of engine may cause some variation in the level at which contrails first form. An example of this effect occurred on 27th October, 1955. A Canberra aircraft first made contrails at 31,500 ft. and ceased to make trails

/at

at 35,000 ft., but an observing Javelin aircraft did not make trails until 31,700 ft. and ceased to make trails at 34,000 ft. Presumably the difference is due to the different engines in the two aircraft, an Avon engine in the Canberra and a Sapphire engine in the Javelin. It was found by A.M. Young (unpublished) that the temperature at which trails are first formed by a Venom aircraft was one or two degrees centigrade below that at which trails are formed by a Canberra.

The effect of relative humidity on the height of the contrail base was also examined and the results are shown in Fig.8. Although there is a slight increase of the temperature at which trails form with increasing humidity, this effect does not seem to be a principal factor in contrail formation but rather a subsidiary controlling factor. This agrees with the results of Murgatroyd (unpublished) as regards contrail formation by Mosquito piston-engined aircraft, and the theoretical results of Appleman (5).

The results of this series of experiments are therefore summarised:-

(1) Temperature is the most important variable in the physical state required for contrails both as regards height of formation and length when formed.

(2) Relative humidity has only secondary effects.

(3) The length of the trail is a complex function of temperature and humidity. A method of estimating the lengths of trails is suggested, based on the experimental data.

(4) Engine setting and type of engine must have some effect on the formation of contrails, but insufficient evidence is at present available to enable any conclusions to be drawn.

Forecasting contrails for Canberra aircraft in southern England

In order to forecast contrails in practice by the use of Fig.5 it is first necessary to estimate the temperature and frost point at a given height. Data on the former are always available from routine radio-sonde ascents. Ref.(6) gives a statistical method of estimating frost point up to 40,000 ft. if the temperature of the tropopause is known, but an alternative method of estimation, using synoptic and statistical data, is given below and is applicable up to 50,000 ft.

Fig.9 is a graph showing the results of 81 high level ascents by aircraft of the Meteorological Research Flight in 1954 and 1955 to measure the humidity of the upper atmosphere. As presented here, all observations above 25,000 ft. were used to derive a relationship between ambient temperature and frost point depression. On this graph are drawn various MINTRA temperatures for selected pressure levels so that frost point depression can be estimated in the form of a band width. Standard deviations of depression of frost point at selected levels are shown in Table II and this combined with Fig.9 will give a first estimate of the frost point depression over southern England at any level for a given ambient temperature. Use can also be made of Ref.(9) which describes the humidity structure of the atmosphere associated with cirrus cloud observations. From this information a good estimate of the humidity structure on any day can be derived.

A forecasting procedure based on these ideas would therefore be

(1) Find the temperatures at levels in the atmosphere for which contrail information is required. Read off the isobaric depression of this temperature from the MINTRA line using the Form 2810A on which the appropriate radio-sonde ascent is plotted.

(2) Use Fig.9, Table II and any synoptic data on high cloud to get an estimate of the frost point depression.

/(3)

(3) Use Fig.5 to find the expected length of the contrail for the values of depression of temperature and depression of frost point obtained in (1) and (2) above.

Conclusion

Although these data are comparatively few, the results as regards levels of formation are in agreement with those previously presented from several sources, e.g., Murgatroyd, Young, and the calculations of Appleman [5] and Godson [10]. It is known that in a few cases there have been reports at lower levels and higher temperatures than any observed by the Meteorological Research Flight but it is considered that these are exceptional.

References

(1) Murgatroyd, Goldsmith and Hollings 1954 Meteorological Research Papers, Air Ministry, London, No.877.

(2) Durbin, W.G. 1955 Meteorological Research Papers, Air Ministry, London, No.930.

(3) Murgatroyd, Goldsmith and Hollings Oct.1954 Q.J.R.Met.Soc., Vol.8, No.350, p.533.

(4) Brewer, A.W. Weather, June, 1946.

(5) Air Weather Service Technical Report, pp.105-112 1953.

(6) Bannon, Frith and Shellard 1952 Geophysical Memoirs, Air Ministry, London, No.88, pp.16-22.

(7) Goldie, A.H.R. 1953 Meteorological Research Papers, Air Ministry, London, No.805.

(8) Murgatroyd and Goldsmith 1953 Meteorological Research Papers, Air Ministry, London, No.832.

(9) Murgatroyd and Goldsmith 1953 Meteorological Research Papers, Air Ministry, London, No.833.

(10) Met. Division of Transport, Canada 1954 C.I.R.Tech. 178.

Table I. Observations of bases and tops of contrails made by Canberra aircraft

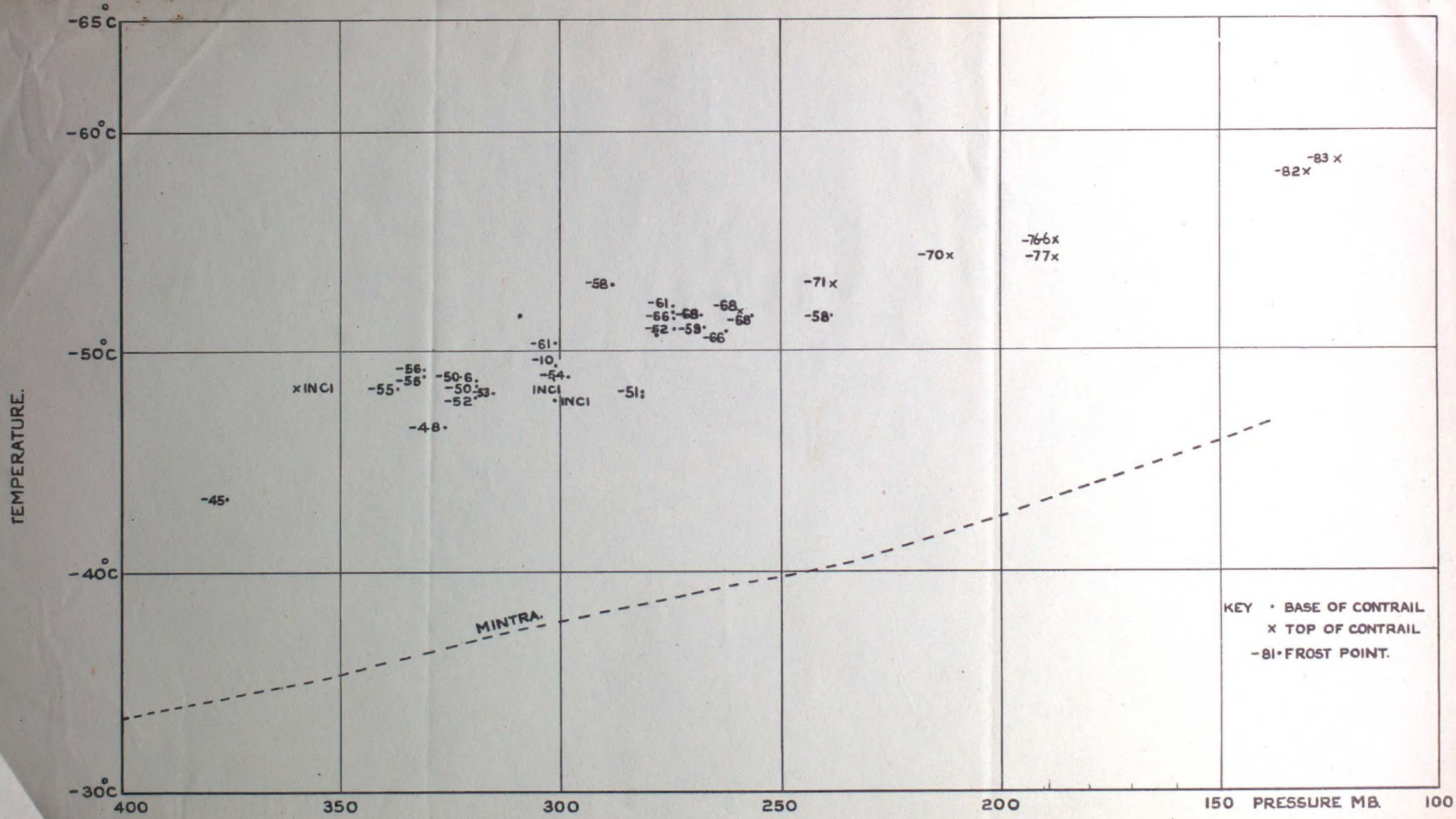
Date	Time GMT.	Method	Base or Top	I.C.A.N. ht. in ft.	Pressure in mb.	Temp. in °C.	Frost Point °C.	R.H. %
4/3/55	1125	1	Base	28,800	319	-48.7	-50.6	79
14/3/55	1140	1	Base	28,700	320	-48.5	-50.0	84
15/3/55	1150	1	Base	28,700	320	-47.9	-51.7	64
16/3/55	1530	1	Base	29,400	309	-51.7	-	-
18/3/55	1605	1	Base	27,900	331	-49.2	-55.6	45
28/3/55	1500	1	Base	27,900	331	-48.9	-55.0	48
"	"	"	"	27,500	337	-48.3	-55.0	44
"	"	"	Layer	25,100	375	-43.3	-45.0	85
29/ 9/55	1445	2	Base	35,000	238	-51.7	-58.1	44
4/10/55	0800	2	Base	32,000	274	-52.1	-61.1	32
12/10/55	1435	2	Base	31,500	281	-48.2	-50.7	74
17/10/55	1045	2	Base	30,000	301	-47.8	in Cirrus	-
26/10/55	1530	2	Base	32,000	274	-51.1	-52.2	87
27/10/55	1555	2	Base	31,500	281	-48.2	-	-
28/10/55	1345	2	Base	29,500	308	-49.4	-60.3	25
1/11/55	1345	2	Base	29,500	308	-50.4	-61.1	25
8/11/55	1345	2	Base	29,000	315	-48.1	-53.6	50
11/11/55	1130	1 & 2	Base	31,000	287	-53.1	-57.7	58
14/11/55	1410	1 & 2	Base	30,400	298	-48.9	-53.9	54
15/11/55	1155	1 & 2	Base	31,700	278	-50.8	-	-
21/11/55	1115	1 & 2	Base	32,100	272	-51.9	-	-
"	"	"	"	32,000	274	-51.6	-66.1	14
22/11/55	1340	2	Base	33,000	262	-51.0	-65.8	14
28/11/55	1330	2	Base	29,500	308	-48.9	in Cirrus	-
29/11/55	1410	2	Base	32,500	267	-51.1	-58.9	36
1/12/55	1125	1 & 2	Base	28,200	326	-46.6	-47.8	87
"	"	"	"	32,500	267	-51.7	-68.3	10
"	"	"	"	33,500	256	-51.7	-68.3	10
"	"	"	"	25,500	368	-47.7	-	-
4/ 3/55	1125	1	Top	47,500	130	-58.2	-82.2	03.2
14/ 3/55	1140	1	Top	48,700	123	-58.8	-83.3	02.7
4/10/55	0800	2	Top	37,500	211	-54.4	-70.0	11.5
8/11/55	1345	2	Top	40,000	187	-54.3	-77.2	04.0
11/11/55	1130	1 & 2	Top	37,700	209	-62.2	-69.4	36.0
1/12/55	1125	1 & 2	Top	33,000	262	-51.9	-68.2	10.1
"	"	"	"	35,000	238	-53.1	-71.1	08.3
"	"	"	"	26,000	360	-48.2	-	-

Relative humidity with respect to ice

Table II. Mean temperature and mean depression of frost point

Height ft.	Mean Temperature °C.	Mean Frost Point Depression °C.	S.d ✱
25,000	-37.3	10.4	8.9
30,000	-47.4	9.3	7.2
34,000	-54.9	9.5	6.8
36,000	-56.1	11.7	7.5
40,000	-55.2	20.3	9.4
44,000	-53.4	27.1	6.0
48,000	-53.1	29.2	6.3

✱ Standard deviation of depression of frost point.



-65°C
-60°C
-50°C
-40°C
-30°C
TEMPERATURE.
400
350
300
250
200
150
PRESSURE MB.
100
MINTRA.
KEY • BASE OF CONTRAIL
× TOP OF CONTRAIL
-81• FROST POINT.

FIG. 1.

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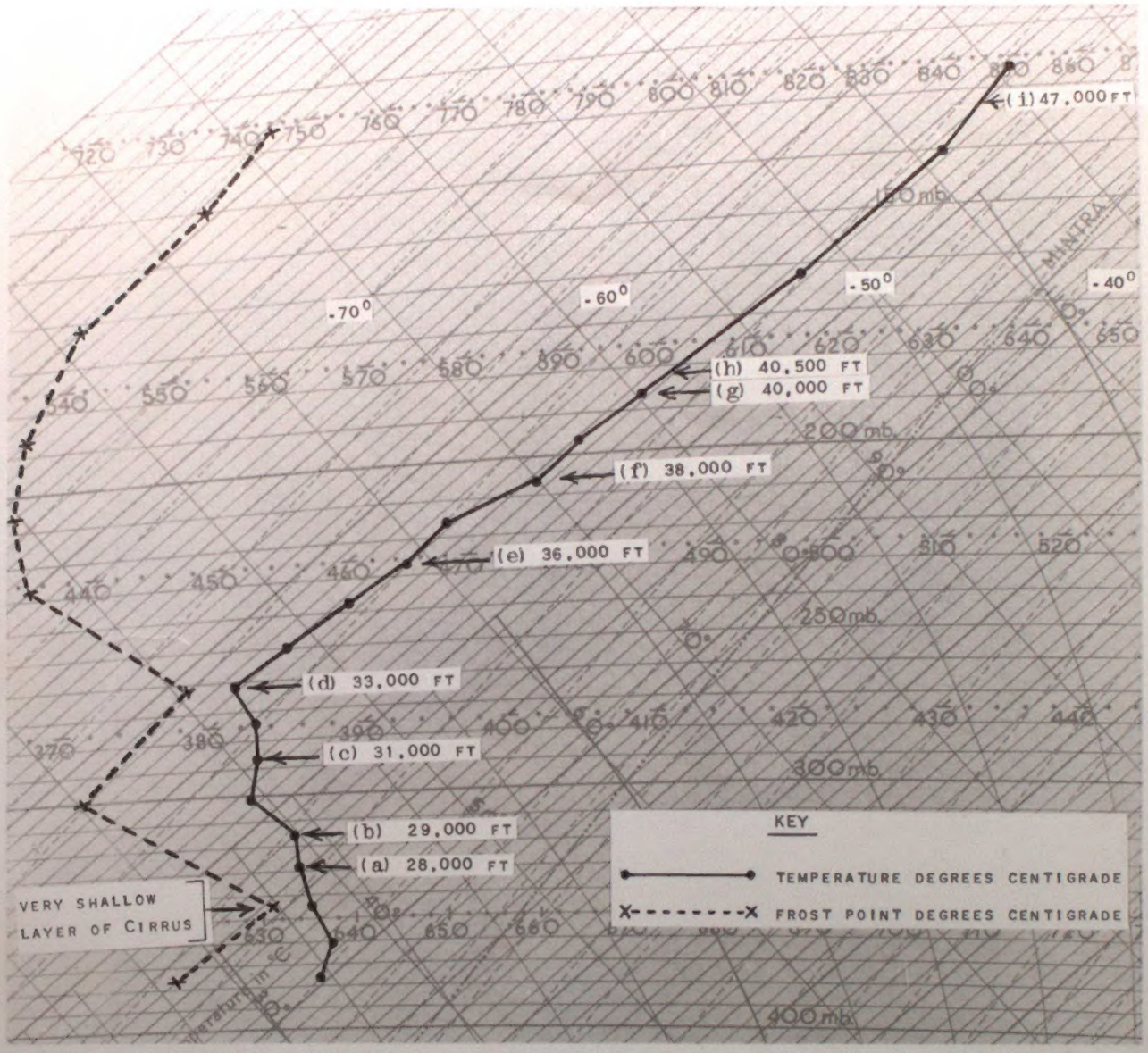
FIG.2a



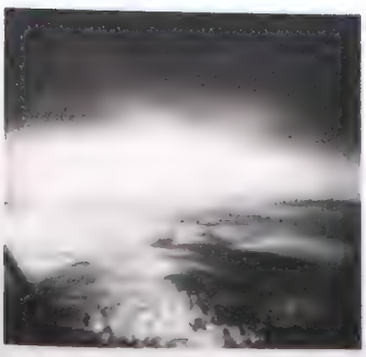
PART OF AIRCRAFT ASCENT ON 8TH NOVEMBER, 1955, TO 48,000 FT. OVER CRAWLEY. ON THIS OCCASION CONTRAILS WERE OBSERVED IN A BAND FROM 29,000 FT. TO 40,000 FT. (I.C.A.O.)

THE CONTRAIL PHOTOGRAPHS ON THE FACING PAGE WERE TAKEN AT THE LEVELS INDICATED BY ARROWS ON THE TEPHIGRAM ABOVE.

FIG.2a

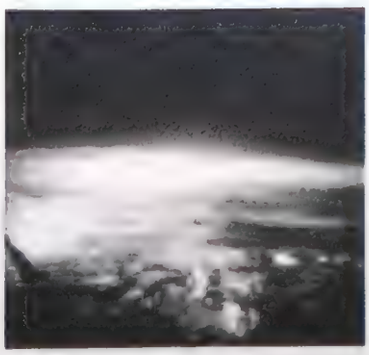
R.A.E. 124601 56

FIG.2b



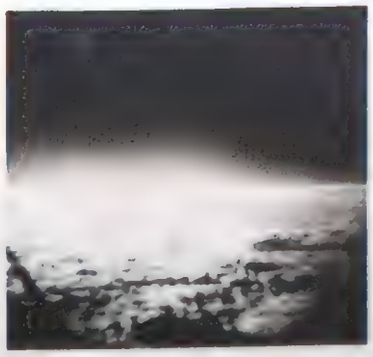
a

2[illegible],500 FEET. NO TRAILS



b

29,000 FEET. TRAILS SHORT AND FAINT.

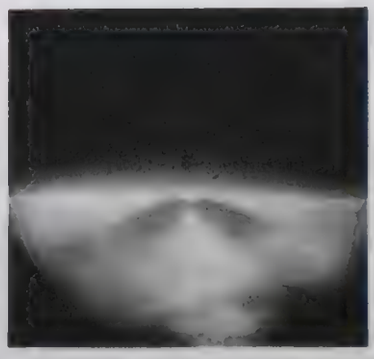


c

31,000 FEET. TRAILS MEDIUM.

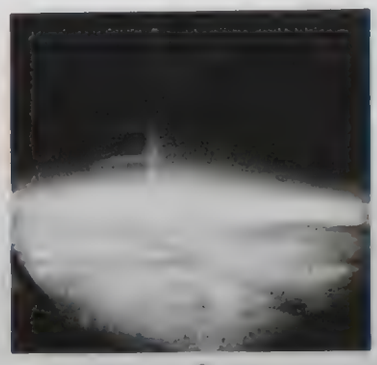
d

33,000 FEET. TRAILS LONG.



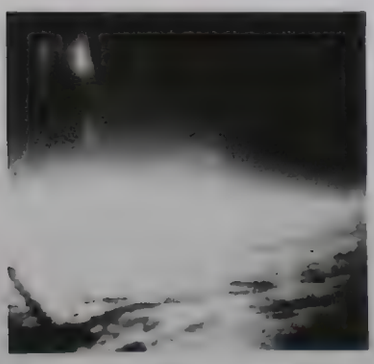
■

36,000 FEET. TRAILS MEDIUM.



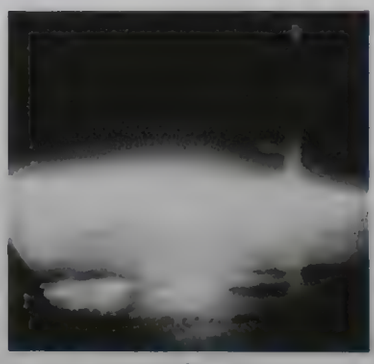
f

38,000 FEET. TRAILS SHORT.



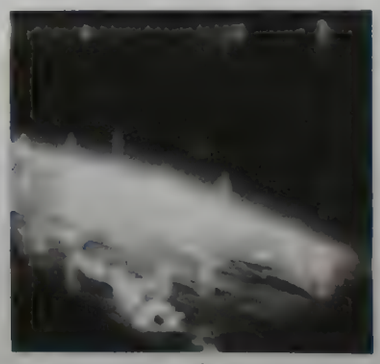
g

40,000 FEET. TRAILS SHORT AND FAINT.



h

40,500 FEET. NO TRAILS.

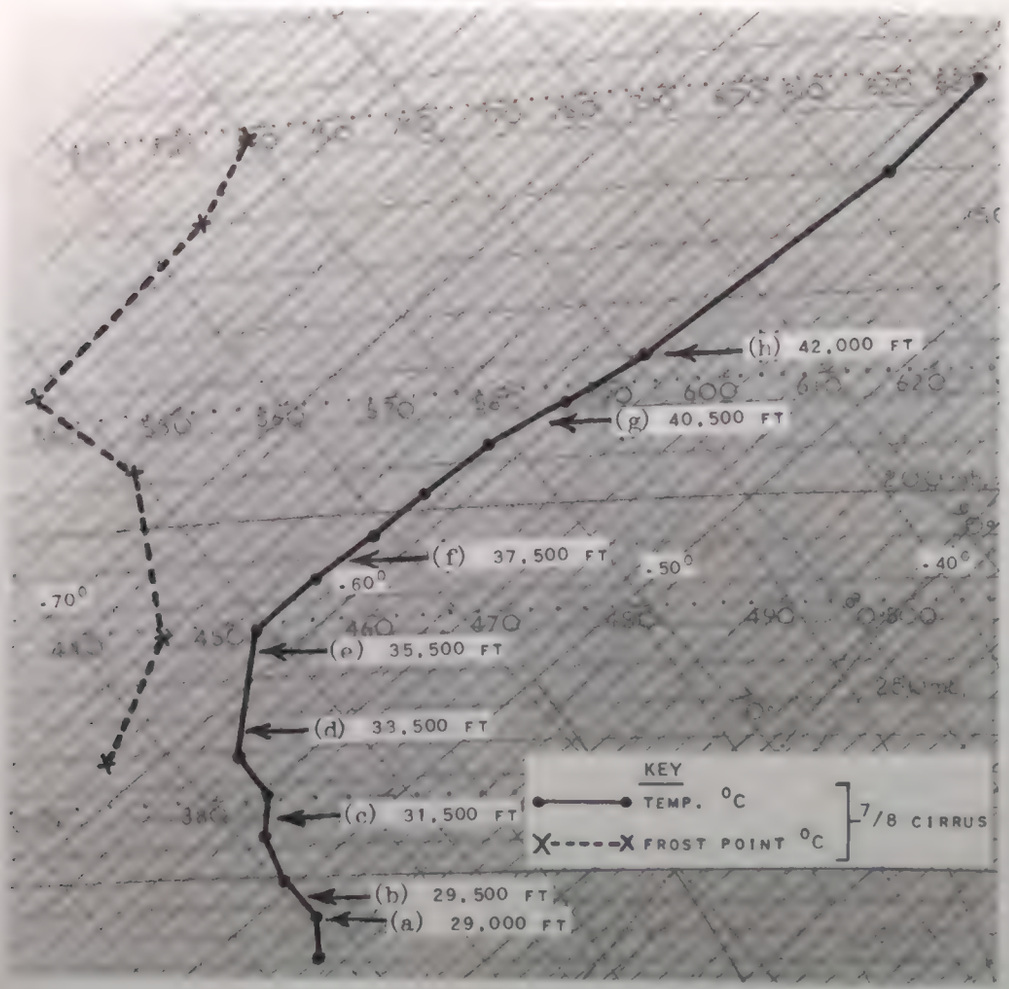


i

47,000 FEET. NO TRAILS.

FIG.2b

R.A.E. 124602 56



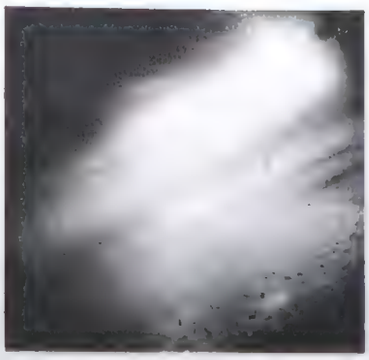
PART OF AIRCRAFT ASCENT ON 28TH NOVEMBER, 1955, TO 48,000 FT. OVER CRAWLEY. ON THIS OCCASION CONTRAILS WERE OBSERVED EVERY 500 FT. FROM 29,500 TO 48,000 FT. (I.C.A.O.) NO TRAILS WERE OBSERVED AT 28,000 TO 29,000 FT.

THE CONTRAIL PHOTOGRAPHS ON THE FACING PAGE WERE TAKEN AT THE LEVELS INDICATED BY ARROWS ON THE TEPHIGRAM ABOVE.

FIG.3a

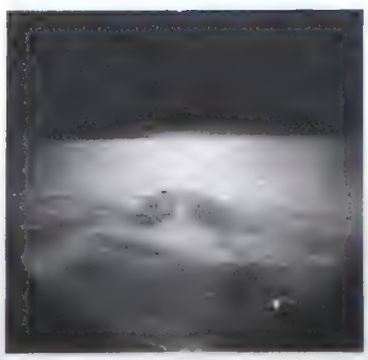
R A E T.2603 S6

FIG.3b



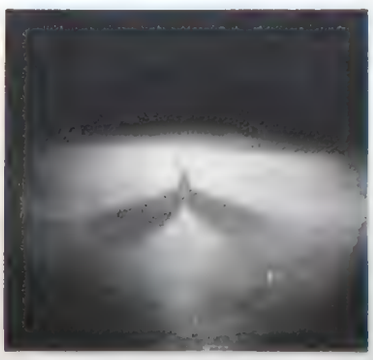
a

[illegible] FEET. [illegible] TRAILS.



b

29,500 FEET. TRAILS LONG.

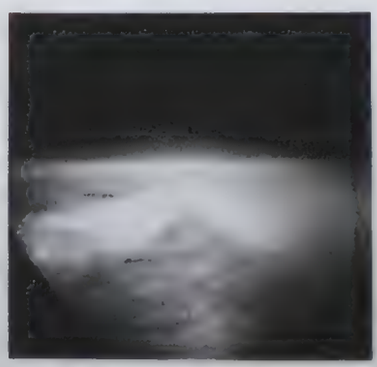


c

31,500 FEET. TRAILS LONG.

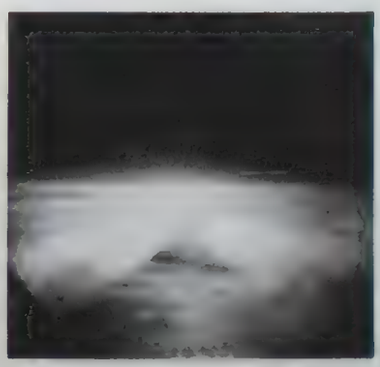
d

[illegible] FEET. TRAILS [illegible].



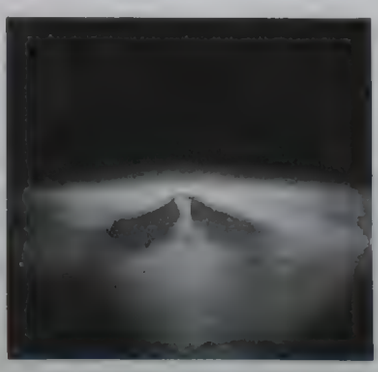
e

35,500 FEET. TRAILS MEDIUM.



f

37,500 FEET. TRAILS [illegible].



g

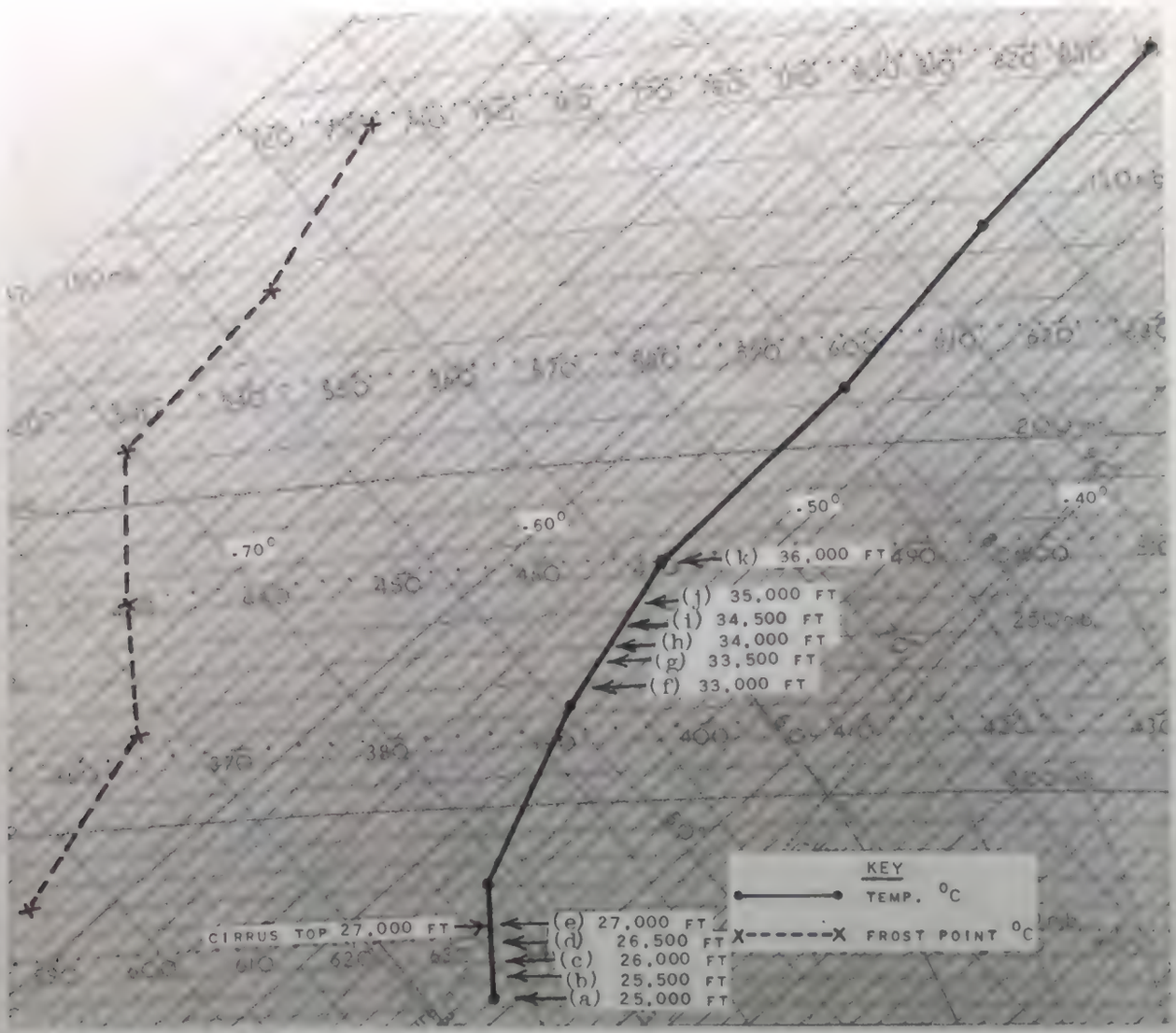
40,500 FEET. TRAILS MEDIUM.

h

42,000 FEET. TRAILS SHORT.

FIG.3b

R A E - 1 3 - 0 4 56



PART OF AIRCRAFT ASCENT ON 1ST DECEMBER, 1955, TO 48,000 FT. OVER CREWE TO HARTLAND POINT. ON THIS OCCASION TRAILS WERE OBSERVED FROM 25,500 FEET TO 26,500 FEET AND FROM 34,000 FEET, 35,000 FEET ONLY. NO OTHER TRAILS WERE NOTED BY ANOTHER AIRCRAFT FLYING IN FORMATION.

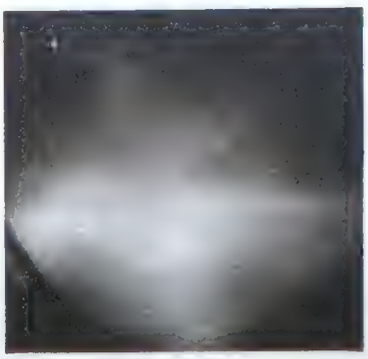
THE CONTRAIL PHOTOGRAPHS ON THE FACING PAGE WERE TAKEN AT THE LEVELS INDICATED BY ARROWS ON THE TEPHIGRAM ABOVE.

FIG.4a

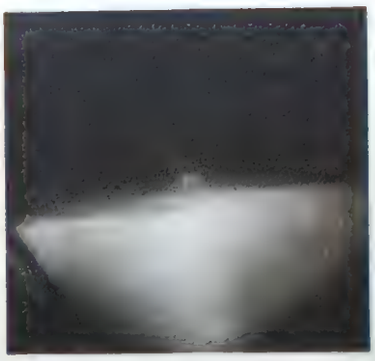
P A E : 24605 56

FIG.4b

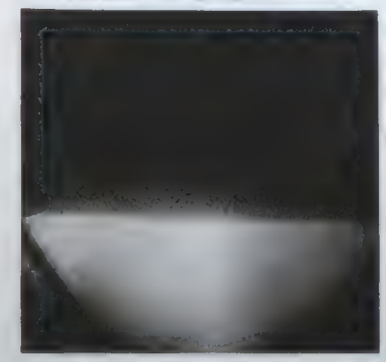
a
25,000 FEET. NO TRAILS VISIBLE IN CLOUD.



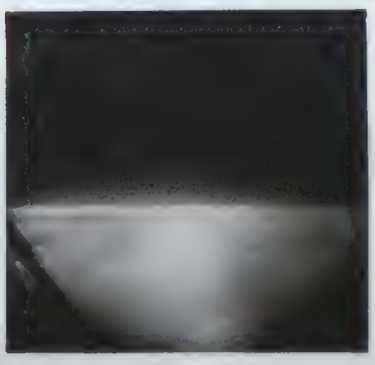
b
25,500 FEET. TRAILS JUST VISIBLE AS TWO DOTS IN CLOUD.



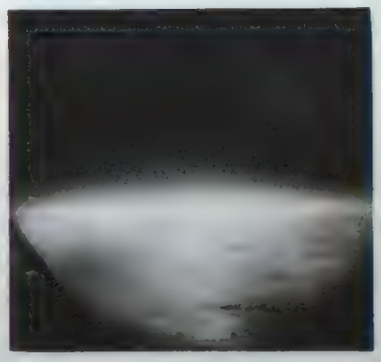
c
26,000 FEET. TRAILS VISIBLE IN CLOUD.



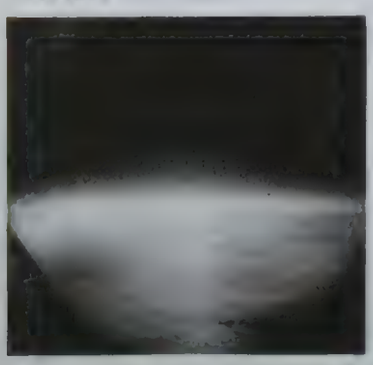
d
26,000 FEET. TRAILS JUST VISIBLE IN CLOUD.



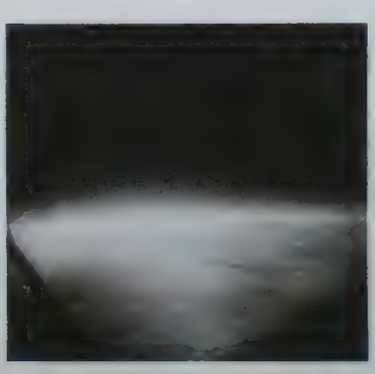
e
27,000 FEET. NO TRAILS.



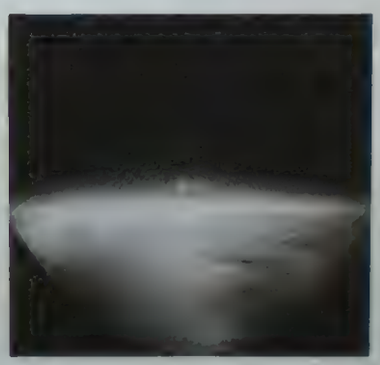
f
33,000 FEET. NO TRAILS.



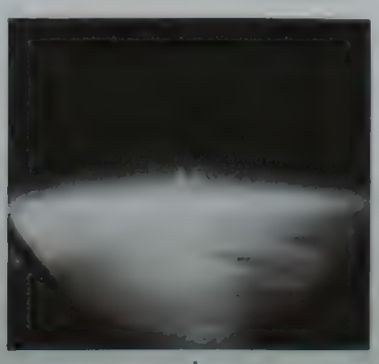
g
33,500 FEET. NO TRAILS.



h
34,000 FEET. TRAILS JUST VISIBLE.



l
34,500 FEET. TRAILS VISIBLE.



j
35,000 FEET. TRAILS JUST VISIBLE.

k
36,000 FEET. NO TRAILS.

FIG.4b

R.A.E. 12604 T.56

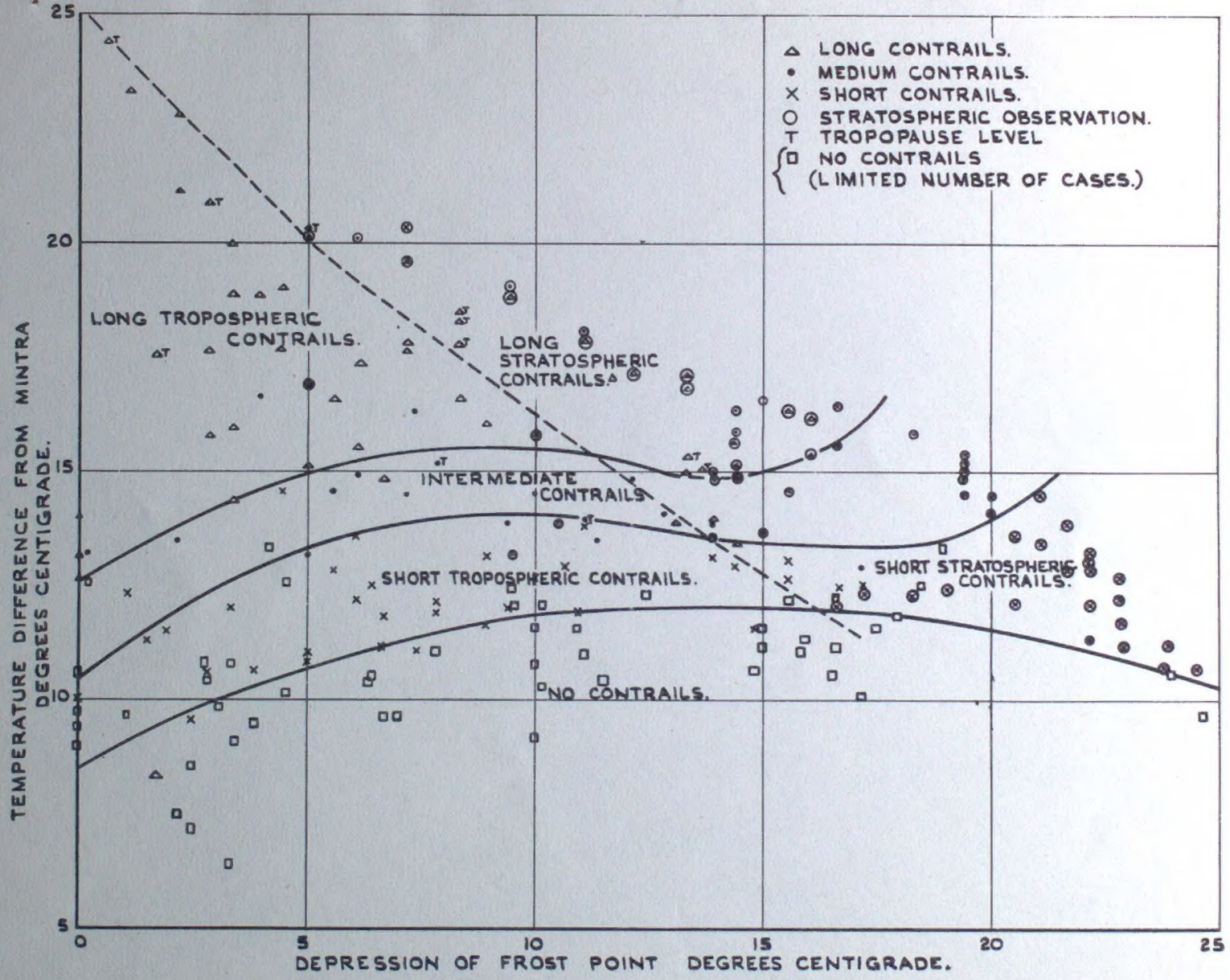


FIG: 5. LENGTH OF CANBERRA CONTRAILS FOR VARYING TEMPERATURE AND HUMIDITY.

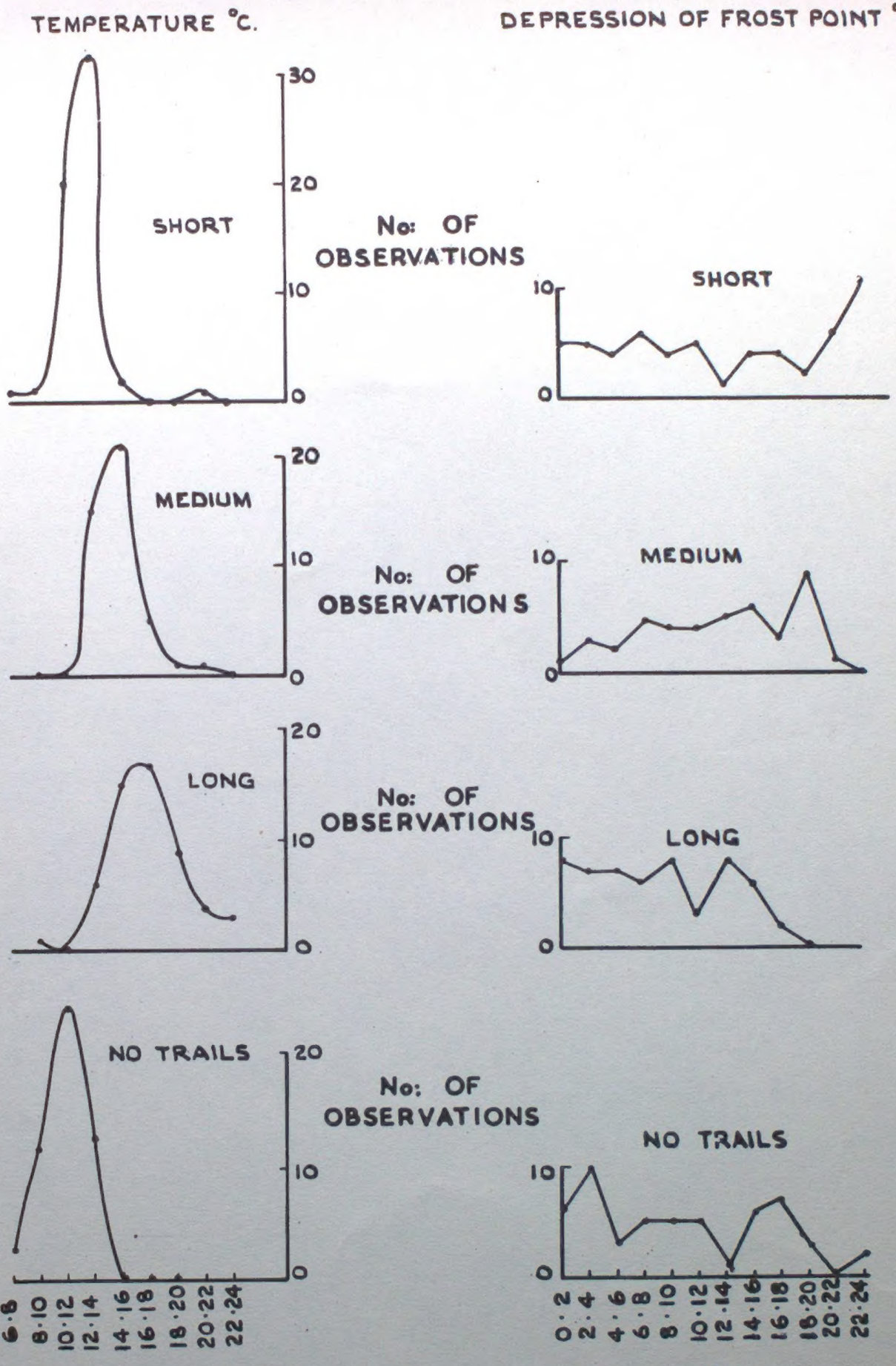


FIG: 6 a & b. FREQUENCY DISTRIBUTION CURVES. OF CONDENSATION TRAILS FROM 1000 FEET BELOW THE BASE TO 1000 FEET ABOVE THE TOP WITH RESPECT TO (a) TEMPERATURE DEPRESSION BELOW MINTRA AND (b) DEPRESSION OF FROST POINT.

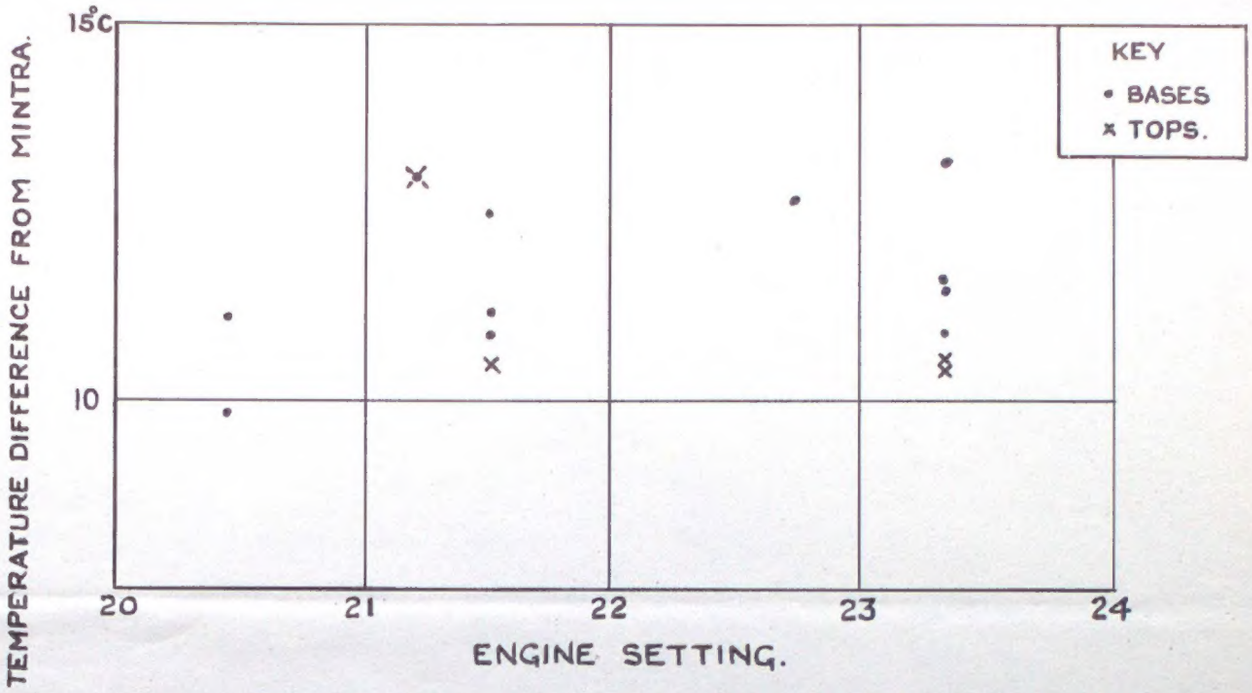


FIG. 7. EFFECT OF ENGINE SETTING ON CRITICAL CONDITIONS FOR CONTRAIL FORMATION.

(ENGINE SETTING IN ARBITRARY UNITS, PROPORTIONAL TO R.P.M.)

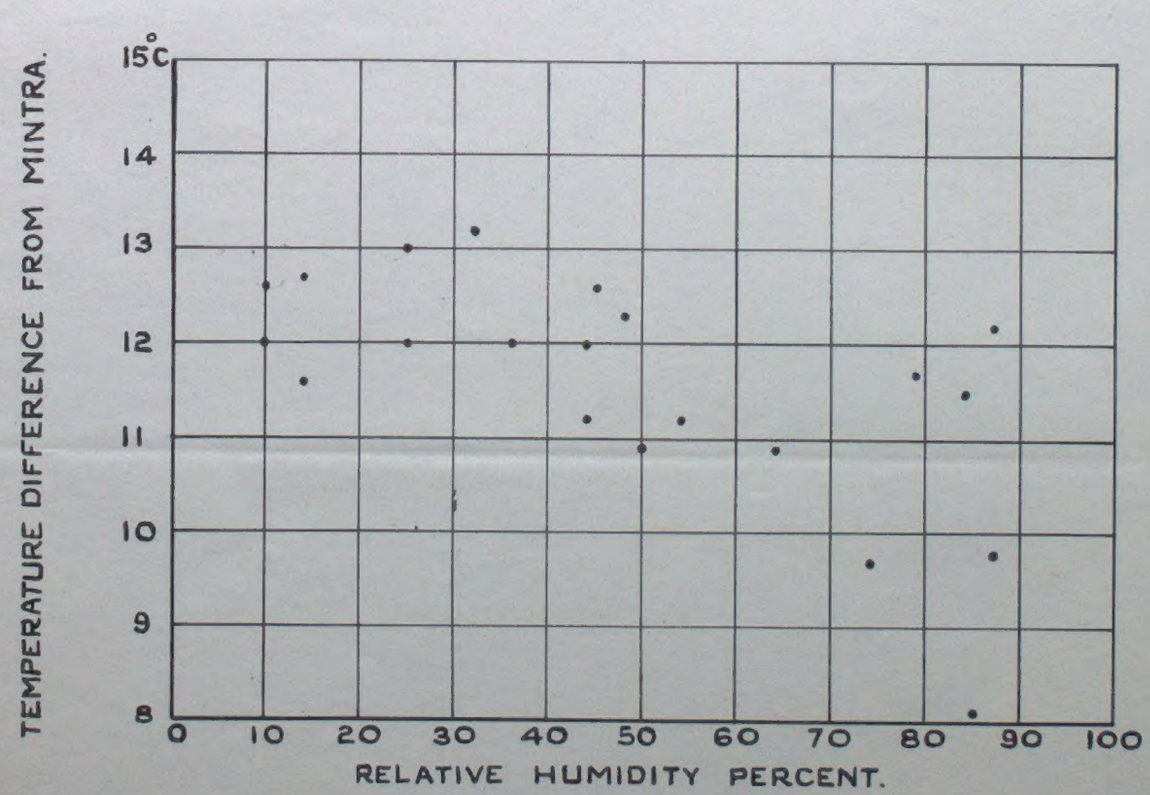


FIG. 8. EFFECT OF RELATIVE HUMIDITY ON TEMPERATURE AT CONTRAIL BASE.

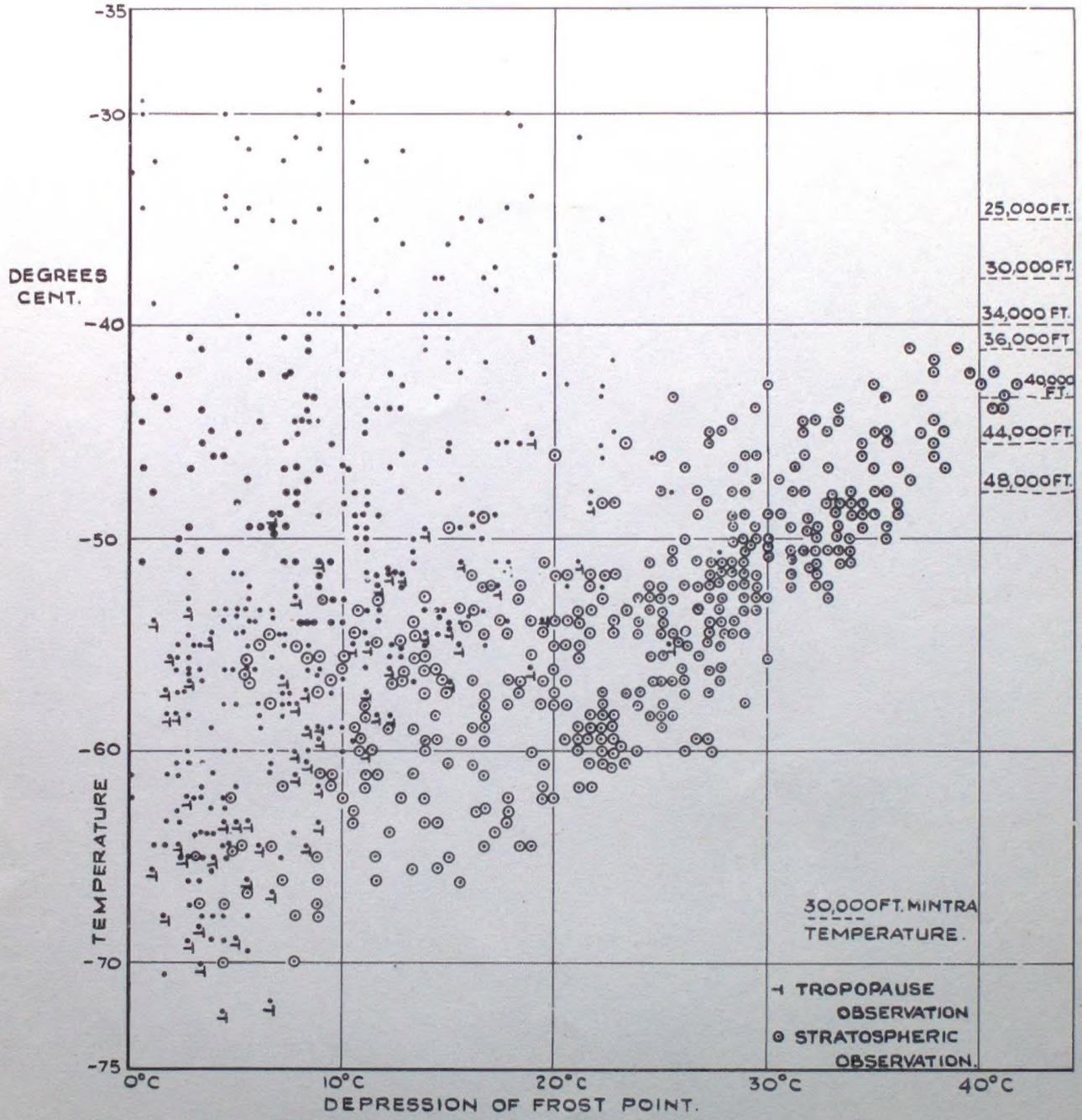


FIG. 9. 81 HIGH LEVEL ASCENTS ABOVE 25000 FT.